A PROPOSED METHOD TO CONTROLLER PARAMETER SOFT TUNING AS ACCOMMODATION FTC AFTER UNKNOWN INPUT OBSERVER FDI

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ABSTRACT

The problem of Fault Tolerant Control (FTC) by the use of methods of fault accommodation and reconfiguration is one of the most updated and versatile problems of modern science in control systems engineering. Occurrence of a fault in every components of a system (actuators, sensors, and internal structure) can remove the control loop from the desired state or even destabilize it. The purpose of the fault tolerant control by the accommodation method is to present operational solutions, by the use of which the control loop stability can be maintained and an acceptable performance is obtained (probably weaker than the no-fault condition) in fault occurrence conditions without the need to shut down the system. In this paper, the fault detection and isolation (FDI) issue has been investigated including the fault of system actuators. Design of a fault detection system for a multi-input multi-output (MIMO) system has been done by the method of Unknown Input Observer (UIO). In this method, the system is divided into several sub-systems in a way that the effects of other inputs are entered into states equations as a disturbance. The design method of the observer is such that the disturbance effect is attenuated and only the fault related to a particular input is detected. Having detected and isolated a fault, controlling coefficients are iteratively updated and modified using an auto-tuning method and the closed loop system stability is ensured in the presence of the method. In addition, in order to reduce the oscillation resulting from exerting momentary changes in controlling coefficient, a modification method known as the Sigma modification has been used. Next, the method is implemented on the favorite model of three tanks and the results confirm capability of the designed fault detection system and quality of auto-tuning of the controller.

Keywords: fault tolerant control, fault accommodation, fault detection and isolation, unknown input observer, sigma modification method.

INTRODUCTION

Taking into account the performance of fault detection and location system (FDI), it is called a system for detection, separation and analysis of faults in which outputs show the occurrence and intensity of faults.

Model Based Fault Detection and Isolation (MBFDI), there are many theories on fault detection and location for linear systems, some of which are the observer based theory, the parity space theory and the parameter estimation theory [14]. Especially recently, the observer based theory has gained a lot of attention. However, the methods mostly deal with a specific class of non-linear problems. This is basically a result of existence of various classes of non-linear systems and also that the system consists of phenomena such as saturation effect or non-analytical behavior [1, 2, 14].

One of the most important issues in the observer based FDI framework is the decomposition of an unknown input. In this respect, the problem of fault separation can be formulated as a problem of unknown input decomposition. For this purpose, the fault is used as the two formats of considered and unconsidered fault [3, 8, 13, 14].

Design of Unknown Input Observer to be used for control objectives is has been the subject of many studies in recent decades. In this case, unknown input observers play the role of immeasurable disturbance of output. The basis of the robust method in fault detection is separation of disturbance from state estimation. Using the reduced order unknown observer theory, the system is divided into two sub-systems and the Leon Berger observer is used to design the residuals. In this case, a residue will be obtained that indicates the occurrence and location of the fault [6, 9]. Furthermore, the PID controller is yet established as a useful and reliable control solution for many industrial processes. Research on new tuning methods is a developing subject. One of the most important advantages of the controllers is that they are implemented as well as regulated and that they give a desirable mediocrity between simplicity and cost [4, 5, 16]. Anyway, their tuning is a wise process. Their tuning process manually takes so much time, and owing to defect in the identification, it is led towards control loops that are regulated poorly [7, 17]. In the past fifty years, many attempts have been made to promote auto-tuning methods to enable PID controllers for auto-tuning [10, 15, 17].

THE UNKNOWN INPUT OBSERVER THEORY

In the methods based on the theory, disturbance is considered as an unknown input. The purpose of design of

Unknown Input Observer is to separate disturbance from the residue. For this purpose, consider a linear dynamic system with the following additive faults:

$$\dot{x}(t) = Ax(t) + Bu(t) + E_2 d(t) + F_2 f(t)$$
$$y(t) = Cx(t) + Du(t) + E_2 d(t) + F_2 f(t) \quad (1)$$

Where $x\epsilon R^n$, $u\epsilon R^m$, $y\epsilon R^p$, E_i and F_i are vector of states, inputs vector, outputs vector, unconsidered faults vector, considered faults vector, respectively, and d and f are their disturbance distribution matrices. Matrices A, B, C and D have also appropriate dimensions.

UIO Definition

For a system with the expressed dynamic equations of (1), the structure of a full rank Unknown Input Observer is as follows [18], [19]:

$$\dot{Z}(t) = Fz(t) + TBu(t) + Ly(t)$$
$$\hat{x}(t) = z(t) + H\,y(t) \quad (2)$$

Where $\hat{x} \in R^n$ and $Z \in R^n$ are the estimated states vector and the full order observer states vector, respectively. The necessary and enough conditions for the existence of such an observer are as follows:

a) rank(CE_1)= rank(E_1).

b) The pair (A_1, C_1) is acquirable by

$$A_1 = A - E_1\big((CE_1)'(CE_1)\big)^{-1}((CE_1)'CA);$$

Or reciprocally transfer of d zeros to the measurement vector of y(t) should be stable. There is a series of degrees of freedom in matrices H, L, T and F that should be adjusted to design the observer described by equations (2). An overview of the observer is shown in the Figure-1.

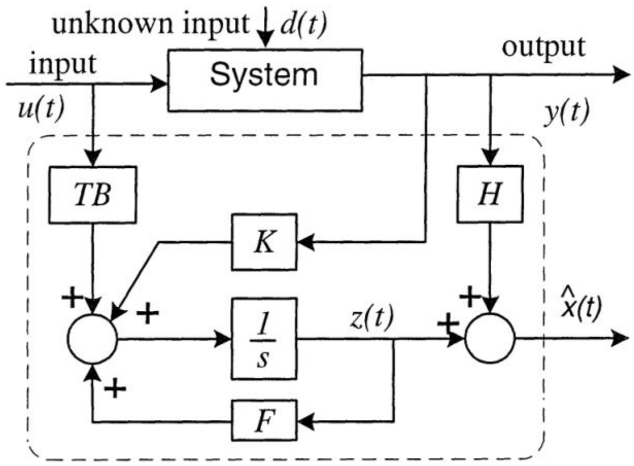

Figure-1. The general scheme of an UIO.

Residual

The fault detection and isolation (FDI) method for continuous systems consists of two stages of generation and evaluation of residual.

Generation of residual

Generation of residual for the model based detection and isolation system is according to the analytical redundancy description. In most approaches, the analytical redundancyis described by a set of differential equations, the purpose is to generate a structured residue to achieve an appropriate FDI. The difference between the process variables and their estimations is called residual and variables can be the system output or parameters.

Main function of an observer based FDI approach is design of a structured observer to detect and isolate considered faults. The existing observer based methods generate estimates that can be created by the existing measurements for obtaining residual. There are many types of observer based approaches including linear and non-linear systems

Evaluation of residual

A successful residue based FDI needs the residue evaluation. Residue evaluation means investigation of residual such that the following decisions are made:

a) Has a fault occurred so far?

b) If yes, which fault or faults have occurred?

Especially, the second decision depends on the fact that whether the faults are single (one at a time) or multiple (simultaneous). Therefore achieving a correct residue structure is important for a correct residue evaluation. Residual should be generated in such a way that a different group of residual takes effect for each fault [14].

Matrices H, L, T and F should be adjusted so that the dynamic system is stabilized and have the following residue. If the fault vector f(t) $\neq 0$, the residue deviates from zero.

$$R(t) = y(t) - \hat{y}(t) = y(t) - C\hat{x}(t) \quad (3)$$
$$= (I - CH)y(t) - Cz(t)$$

The condition of $Tf_1 \neq 0$ should be met for the actuator faults. The observer designed for the system is a Leon Berger observer.

For a system with the following states space equations

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) \quad (4)$$

The Leon Berger observer equations are according to equation (5), in which L should be found.

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$$\dot{x}(t) = A\hat{x}(t) + Bu(t) + L\big(y - C\hat{x}(t)\big) = (A - LC)\hat{x}(t) + Ly(t) \tag{5}$$

PROBLEM FORMULATION

As was mentioned, in order to demonstrate the UIO theory application, we will use the favorite system of three tanks. The model for the non-linear tank system with two pumps is as follows [20]:

$$\begin{aligned} A\dot{x}_1 &= u_1 + R_{13}p(x_1, x_3) + \Delta Q_1 \\ A\dot{x}_2 &= u_2 + R_2 p(x_2, 0) + R_{32}p(x_3, x_2) + \Delta Q_2 \\ A\dot{x}_3 &= R_{13}p(x_1, x_3) + R_{32}p(x_3, x_2) \end{aligned} \tag{6}$$

Where $x_i=h_i$, $u_i=Q_i$, and coefficients R_{13}, R_2 and R_{32} is respectively level of water, internal flux and the valves between the tanks V_1, V_2 and V_3, while the function the function $p(x_i,x_j)$ is equal to $\mathrm{sgn}(x_i-x_j)\mathrm{sqrt}(2g(x_i-x_j))$.Fault are considered as constant deviations of pumps flows and there are two types of actuators in the model, defined as ΔQ_1 and ΔQ_2, each of which are affected by the faults at different times. For each one of faults an observer and as a result a residue is designed in such a way that when a fault occurs in the first actuator, that is the first pump, one of the residual should be sensitive against the fault in the first pump and insensitive to the second pump, while when a fault occurs in the second actuator, that is the second pump, the other residue should be sensitive to the fault in the second pump and insensitive to the first pump.

Linearizing the system stated in equation (6) around the working point (x^*, u^*), matrices of the model are expressed as follows to reach the described structure.

$$A = \begin{bmatrix} -0.0118 & 0 & 0.0118 \\ 0 & -0.0239 & 0.0123 \\ 0.0118 & 0.0123 & -0.0241 \end{bmatrix},$$

$$B = \begin{bmatrix} 64.9 & 0 \\ 0 & 64.97 \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

And vectors corresponding to the faults of the first and second actuators are respectively as follows:

$$F_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, F_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

Where $[m^3/s]u_1^* = 2.64 \times 10^{-5}$, $[m^3/s]u_2^* = 2.487 \times 10^{-5}$, $[m]x_1^* = 0.2964$, $[m]x_2^* = 0.147$, $[m]x_1^* = 0.22$, $R_{13} = 3.091 \times 10^{-5}$ and $R_{32} = 2.3111 \times 10^{-5}$.

FAULT DETECTION AND ISOLATION

In order to explain the residual, the main system should first be divided into two sub-systems. This problem is put in the design area of reduced unknown input observer. The main idea of designing the FDI observer is to separate observable sub-systems from the main system. Then, in the sub-systems, a full ranked observer is designed based on the equations described in (2) for the faults appearing on time, and as a result, a residue will be maked for each of the measured equations of the sub-systems.

According to the steps reported in [21] for the group of models *(A, B, C, D, E_1, F_1)*, $E_1=F_1$, the following sub-system is provided with the output infusion of y_3 that is independent of faults in the actuator u_2.

$$\begin{aligned} \dot{x}_1 &= -0.0118x_1 + 64.97u_1 + 0.0118y_3 \\ y_1 &= x_1 \end{aligned} \tag{7}$$

The sub-system will let an observer sensitive to faults in the first actuator to be designed.

Now, the designed observer for the sub-system described in equation (7) is as follows:

$$\begin{aligned} \dot{\hat{x}}_1 &= -0.0118\hat{x}_1 + 0.0118y_3 + 64.9u_1 + L_1(y_1 - \hat{x}_1) \\ &= (-0.0118 - L_1)\hat{x}_1 + 64.97u_1 + L_1 y_1 \end{aligned}$$

Selecting L_1=1, the above equation will be stated as follows:

$$\begin{aligned} \dot{\hat{x}}_1 &= -0.0118\hat{x}_1 + 0.0118y_3 + 64.9u_1 + y_1 \\ \hat{y}_1 &= \hat{x}_1 \end{aligned} \tag{8}$$

The observer is the same as one described in equation (2), in which $\begin{cases} z \to x_1 \\ \hat{x} \to \hat{y}_1 \end{cases}$. As a result, according to these conversions and considering equations (7) and (8), the residue generated for the first actuator fault is as follows:

$$R_1 = y_1 - \hat{y}_1 \tag{9}$$

Similarly, in order to detect the faults in the second actuator, another residue should be generated that is insensitive to faults in the first actuator. Thus, similarly, another sub-system is obtained from the main system as:

$$\begin{aligned} \dot{x}_1 &= -0.0239x_2 + 64.97u_2 + 0.0123y_3 \\ y_2 &= x_2 \end{aligned} \tag{10}$$

Where the infusion of the output y_3 is independent of the faults in the actuator u_1. Then, the observer corresponding to the sub-system is designed in accordance with the following equation:

$$\begin{aligned} \dot{\hat{x}}_2 &= -0.0239\hat{x}_2 + 0.0123y_3 + 64.97u_2 + L_2(y_2 - \hat{x}_2) \\ &= (-0.0239 - L_2)\hat{x}_2 + 64.97u_2 + L_2 y_2 \end{aligned}$$

Choosing L_2=1, the above equation is stated as follows:

$$\begin{aligned} \dot{\hat{x}}_2 &= -1.0239\hat{x}_2 + 0.0123y_3 + 64.97u_2 + y_2 \\ \hat{y}_2 &= \hat{x}_2 \end{aligned} \tag{11}$$

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As a result, the following output estimation plays the role of residue for the second pump.

$$R_2 = y_2 - \hat{y}_2 \tag{12}$$

The three tank system is controlled by the PID controller in such a way that in case of occurrence of a fault in each actuator and disruption of each one of the controllers, another controller will guarantee the closed loop system stability (Figure-2).

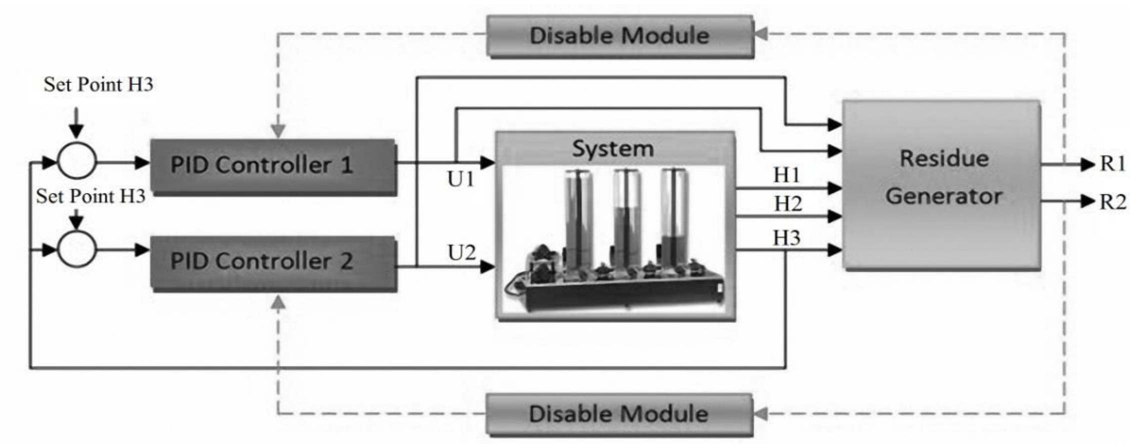

Figure-2. Two controllers scheme with deactivation function produced by the residual evaluation.

In order to evaluate the residual described for the two sub-systems, the system was simulated in the open loop mode. Figure-3 shows the evaluation of the residue R_1 when a fault has occurred in the first actuator while the second residue has remained zero. Figure-4 shows the evaluation of the residue R_2 when a fault has occurred in the second actuator while the first residue has remained zero. Similarly, or the closed loop mode, Figure-5 and Figure-6 express the evaluation of residual R_1 and R_2 when a fault occurs in the first and second actuator respectively. For this system, the instant of occurrence of the fault is t=5000 s and coefficients of the first and second PID controllers is respectively as:

$k_{p1} = 0.00015,\ k_{i1} = 0.0000025,\ k_{d1} = 0.0005$
$k_{p1} = 0.00009,\ k_{i1} = 0.0000011,\ k_{d1} = 0.0005.$

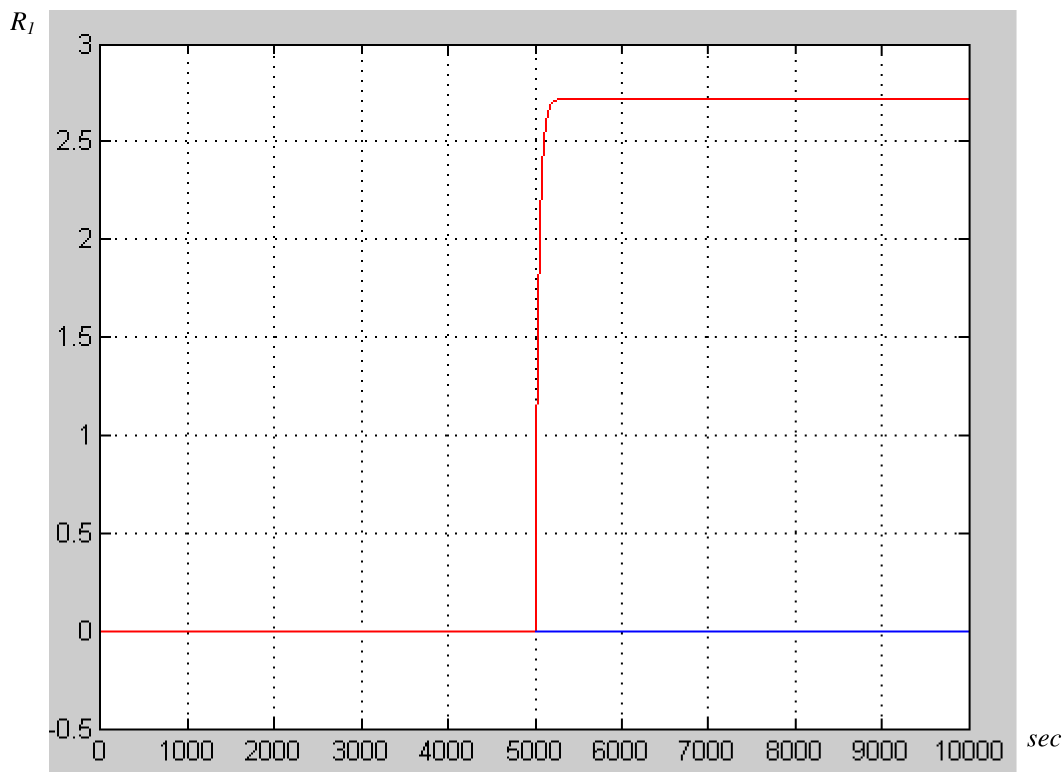

Figure-3. Residual R_1/ open-loop system/ first actuator fault.

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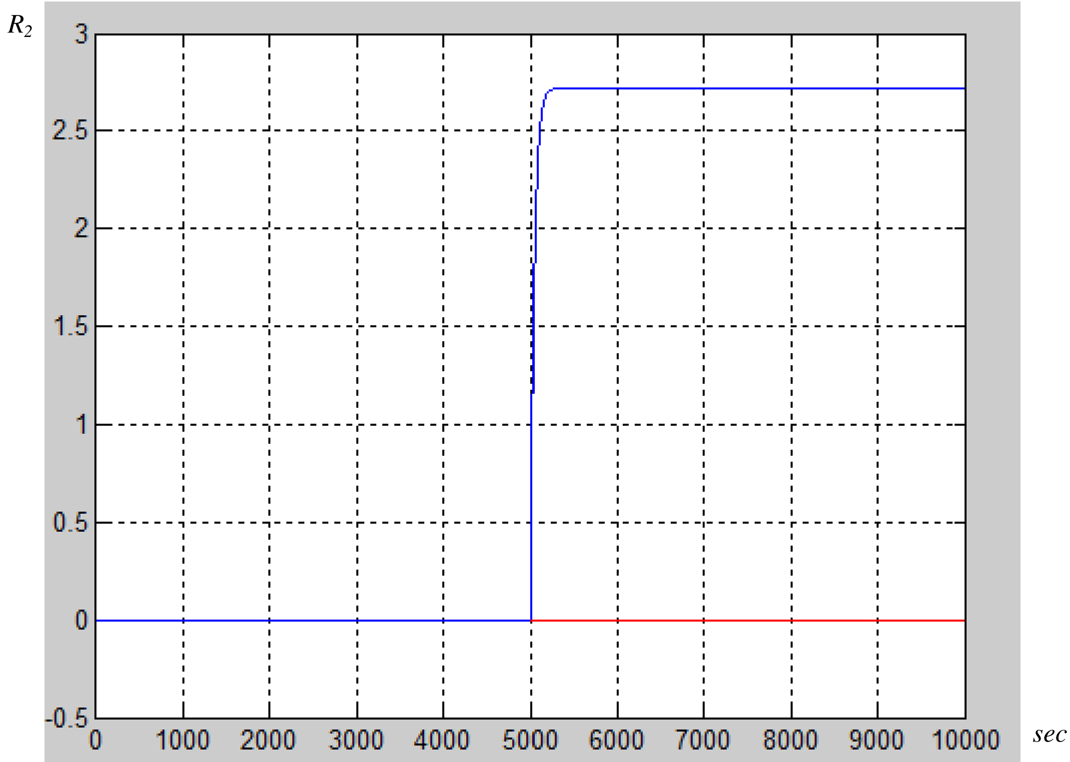

Figute-4. Residual R_2/ open-loop system/ Second actuator fault.

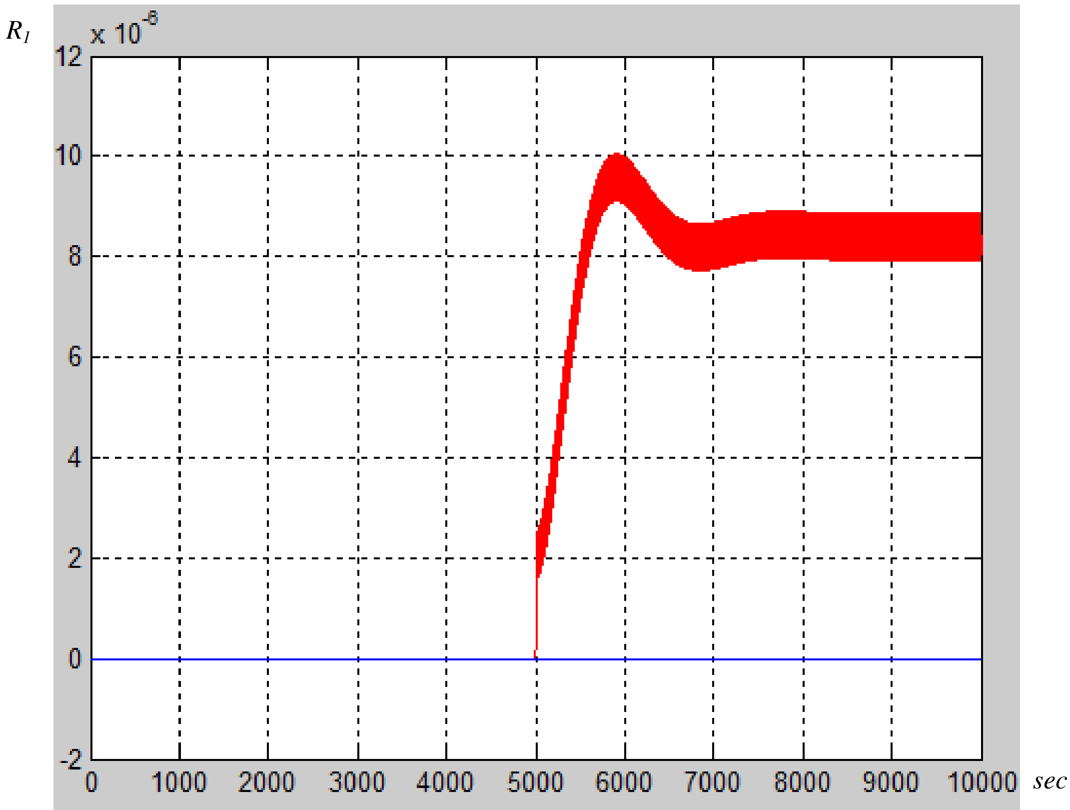

Figure-5. Residual R_1/ closed-loop system/ first actuator fault.

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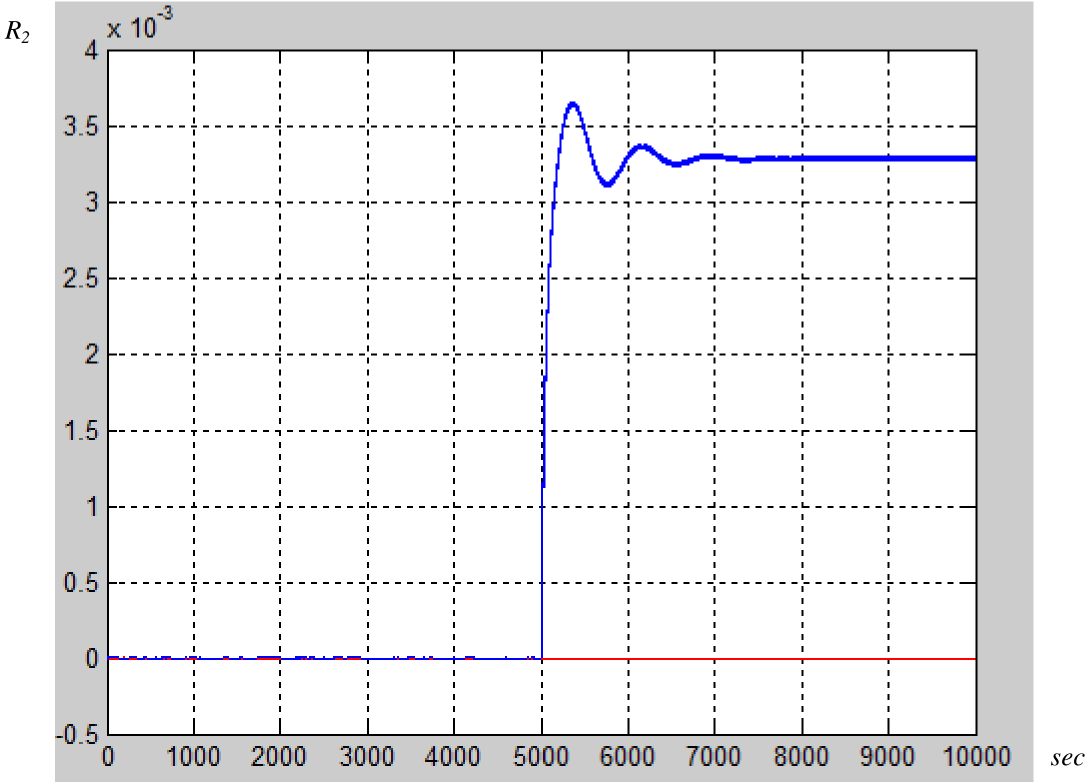

Figure-6. Residual R_2/ closed-loop system/ second actuator fault.

According to results of [18] the FDI method which is used here has caused the sharp decline of FDI duration and consequently, the controller can start up auto-tuning and accommodation.

CONTROL ACCOMMODATION

In An auto-tuning method should meet the following criteria:

a) Have an auto-tuning close the optimum PID controller
b) Guarantees stability for the control system by the use of three adjustable parameters of the PID controller.

Consider the following structure of a PID controller:

$$u = k_p^e + k_i \int e + k_d e' \tag{13}$$

Where e is the system error that is as follows:

e =desirable value-measured value (14)

k_p, k_i and k_d are parameters of the controller that should be selected to approach zero. Now, we express an auto-tuning method for the PID controller. At first, the method is expressed for a single input, single output system and then, it is generalized for a multi-input multi-output system with two PID controllers. Consider a single-input single-output system, described by following state equations:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + bu(t) \\ y(t) &= c^T x(t) \end{aligned} \tag{15}$$

Assume that the equation is met by the following condition.

There are positive definite models $P = P^T > 0$ and $Q = Q^T > 0$ such that

$$\begin{aligned} (A - k_p^* bc^T)^T P + P\left(A - k_p^* bc^T\right) &= -Q \\ pb &= c \end{aligned} \tag{16}$$

For all $k_p^* > 0$ [18, 11, 12].

The system stated in (15) can be stabilized by the following PID controller [18].

$$\begin{aligned} u^* &= -k_p^* y - k_D^* \dot{y} - k_i^* w \\ \dot{w} &= y \end{aligned} \tag{17}$$

Where $k_{\mathrm{p}}^* > 0$, $k_{\mathrm{D}}^* > 0$ and $k_{\mathrm{i}}^* > 0$.

If equation (15) meets $P = P^T > 0$ and $Q = Q^T > 0$, stable PID controller in accordance with (16) can be obtained. Based on the results of (16), It can be showed that the PID controller can be formed even if the system parameters are unknown. Assume that equation (15)

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meet $P = P^T > 0$ and $Q = Q^T > 0$, Then the controller described by equation (21) stabilizes the system.

$$u(t) = -k_p(t)y - k_D(t)\dot{y} - k_i(t)w \qquad (18)$$
$$\dot{w} = \dot{w}(t) = y(t)$$

Here, the PID gains, that is k_p(t), k_d(t) and k_i(t), are adjusted according to the following adaptive gain regulation rule.

$$k_p(t) = \gamma_1 y^2(t)$$
$$k_d(t) = \gamma_2 y(t) y(t) \qquad (19)$$
$$k_i(t) = \gamma_3 y(t) w(t)$$

y_1, y_2 and y_3 are positive constants.

It has been clarified that the adaptive gain rule is not robust against the modeled dynamics. In order to reduce the oscillation resulting from exerting momentary changes in the controller coefficients, a modification method known as the Sigma modification has been used. In these cases, the robust adaptive gain rule is given in equation (20).

$$k_p(t) = \gamma_1 y^2(t) - \sigma k_p(t)$$
$$k_D(t) = \gamma_2 y(t) y\,(t) - \sigma k_D(t) \qquad (20)$$
$$k_i(t) = \gamma_3 y(t) w\,(t) - \sigma k_i(t)$$
$$\sigma > 0$$

Given the step response nature of input, Figure-7 shows the second controller output u_2, before and after the fault occurrence at t=5000 s. In the Figure-7, with the occurrence of the fault in the second actuator, the second controller output will become zero and this is the time when the first controller coefficients should automatically be tuned.Figure-8 shows the output before and after the fault occurrence when the auto-tuning algorithm is implemented. Figure-9, Figure-10 and Figure-11 show the process of auto-tuning of the first controller for k_{I1} with $\gamma_1 = 0.005$, $\sigma = 270$ and for k_{D1} with $\gamma_1 = 0.001$ $\sigma = 350$.

In addition, the control and system outputs after implementation of the auto-tuning method are respectively shown in Figure-12 and Figure-13. In Figure-13, having implemented the auto-tuning method, the control output will have the value of one after the fault occurrence. Figure-14 shows the output after the implementation of the auto-tuning method of the second controller as a result of a fault occurrence in the first actuator.

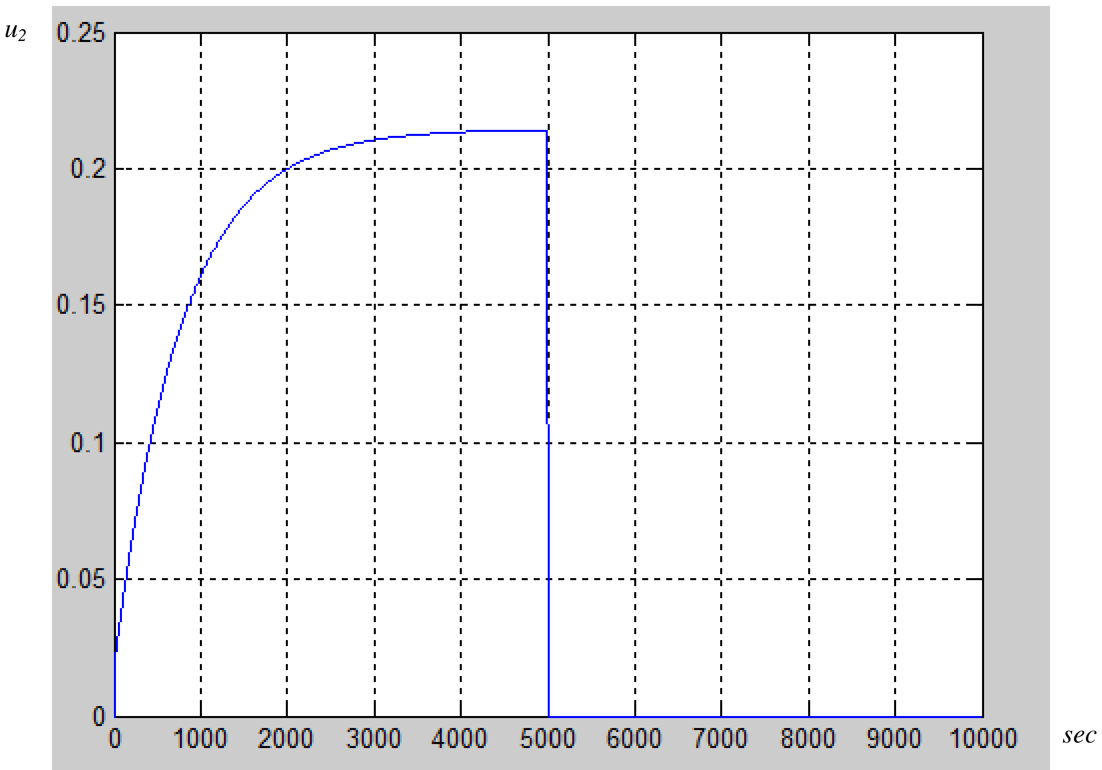

Figure-7. u_2 / fault occurrence (t=*5000 s*) on second actuator.

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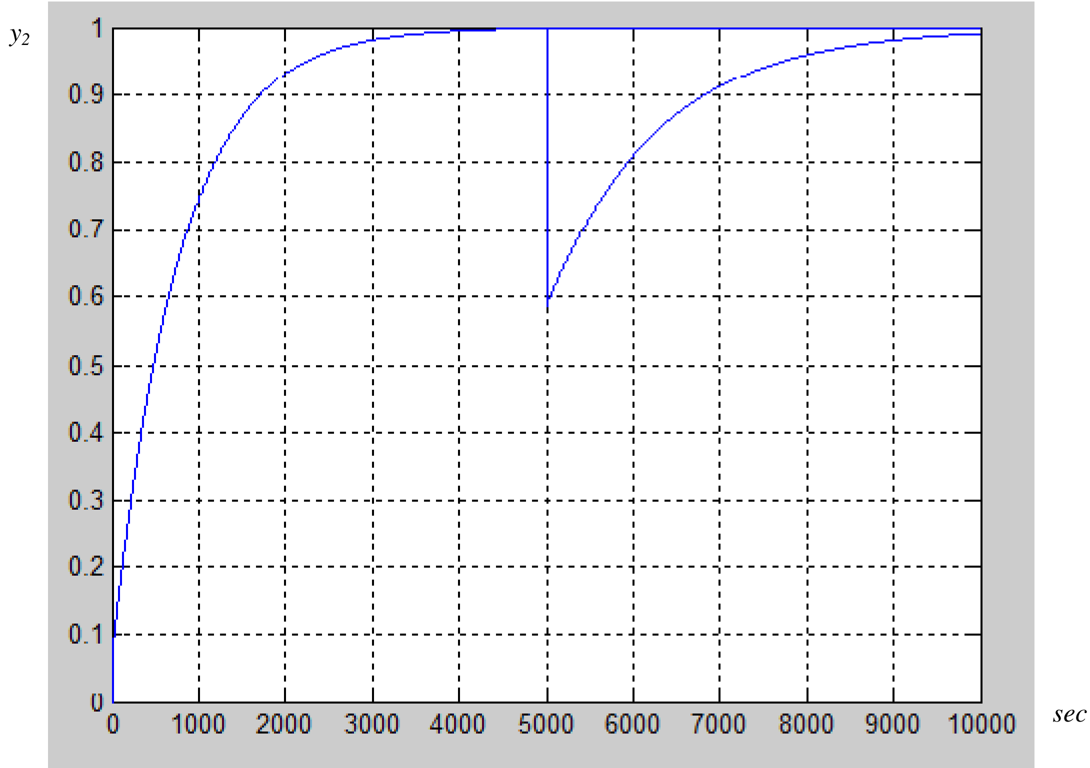

Figure-8. y_2 / fault occurrence (t=*5000 s*) on second actuator.

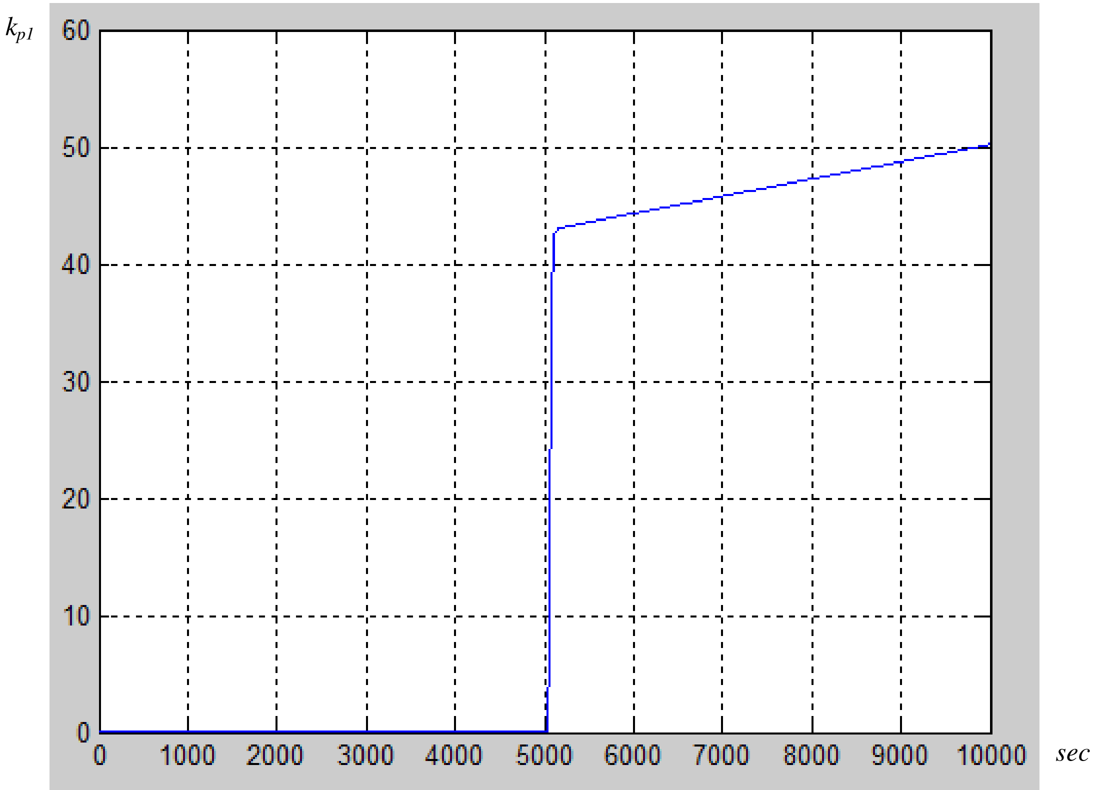

Figure-9. k_{p1} auto-tuning process.

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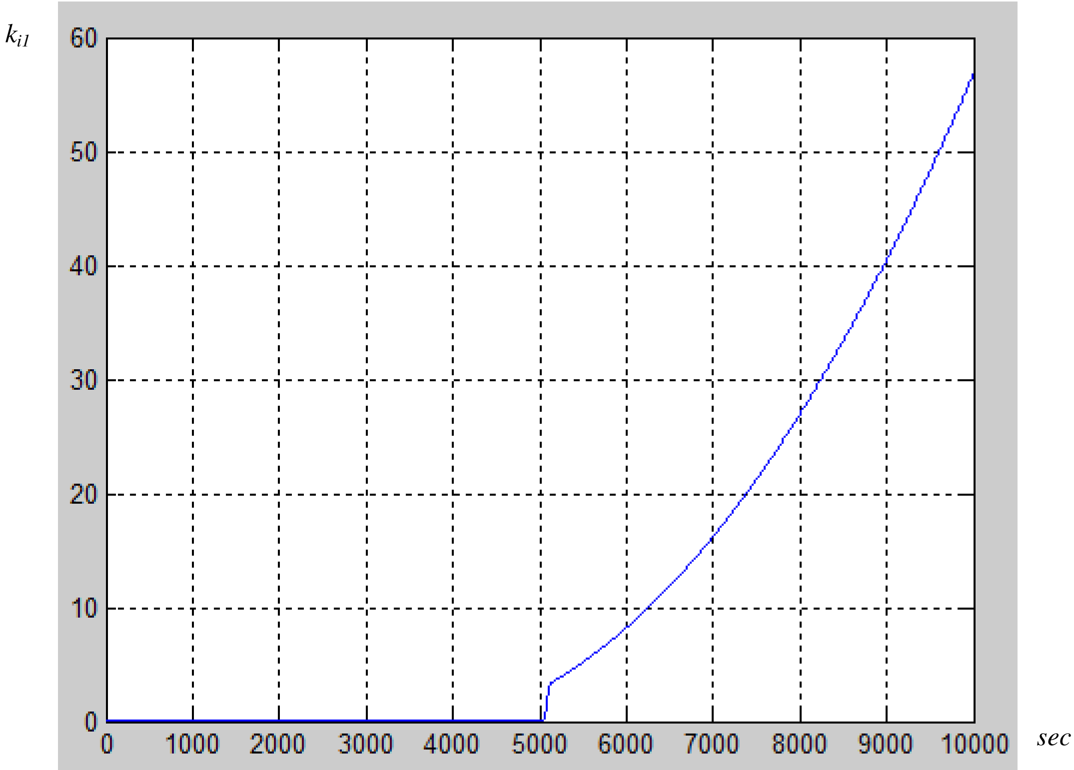

Figure-10. k_{i1} auto-tuning process.

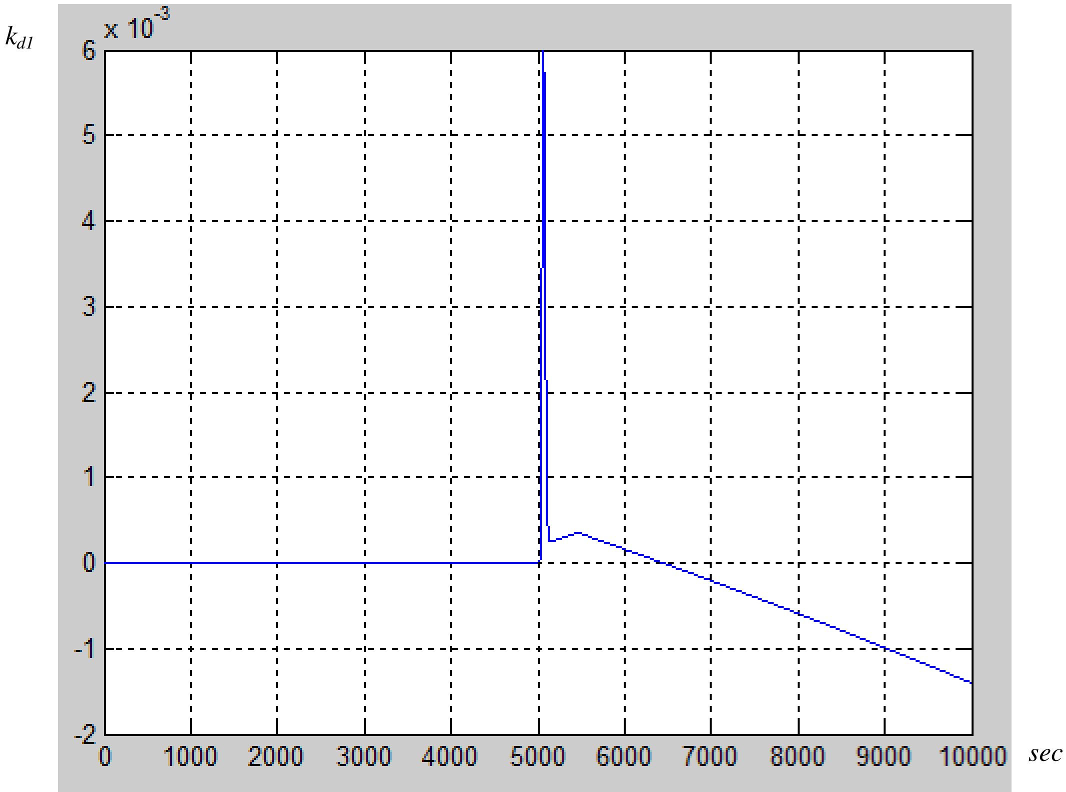

Figure-11. k_{d1} auto-tuning process.

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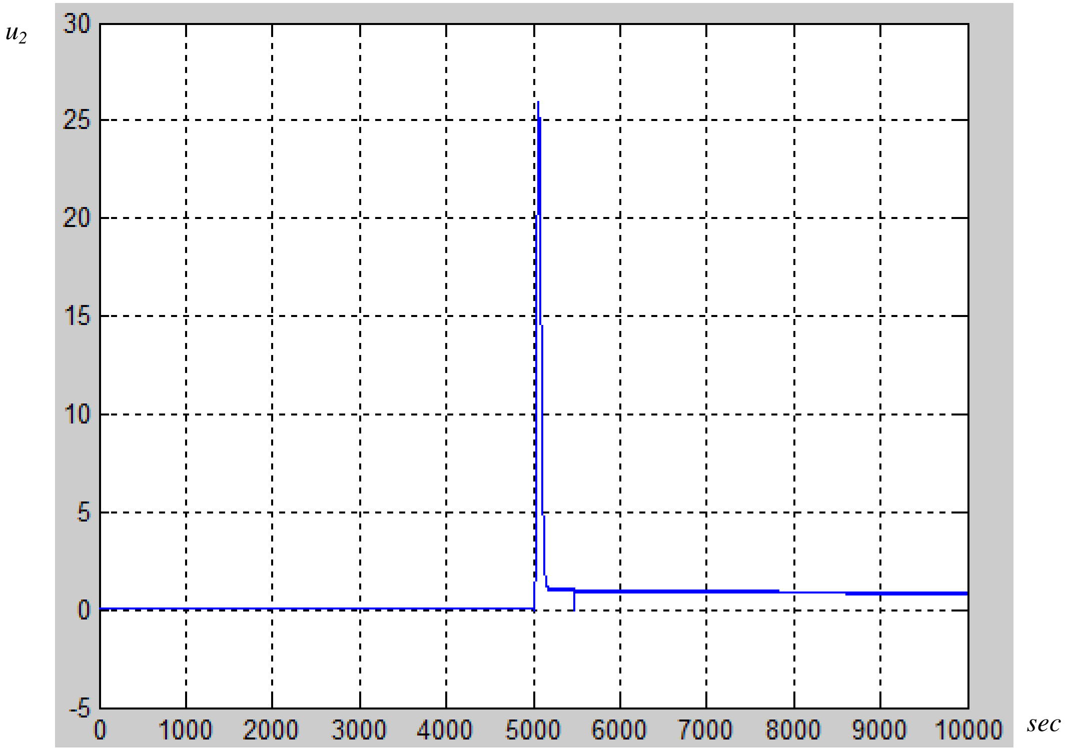

Figure-12. u_2 after fault accommodation and reconfiguration.

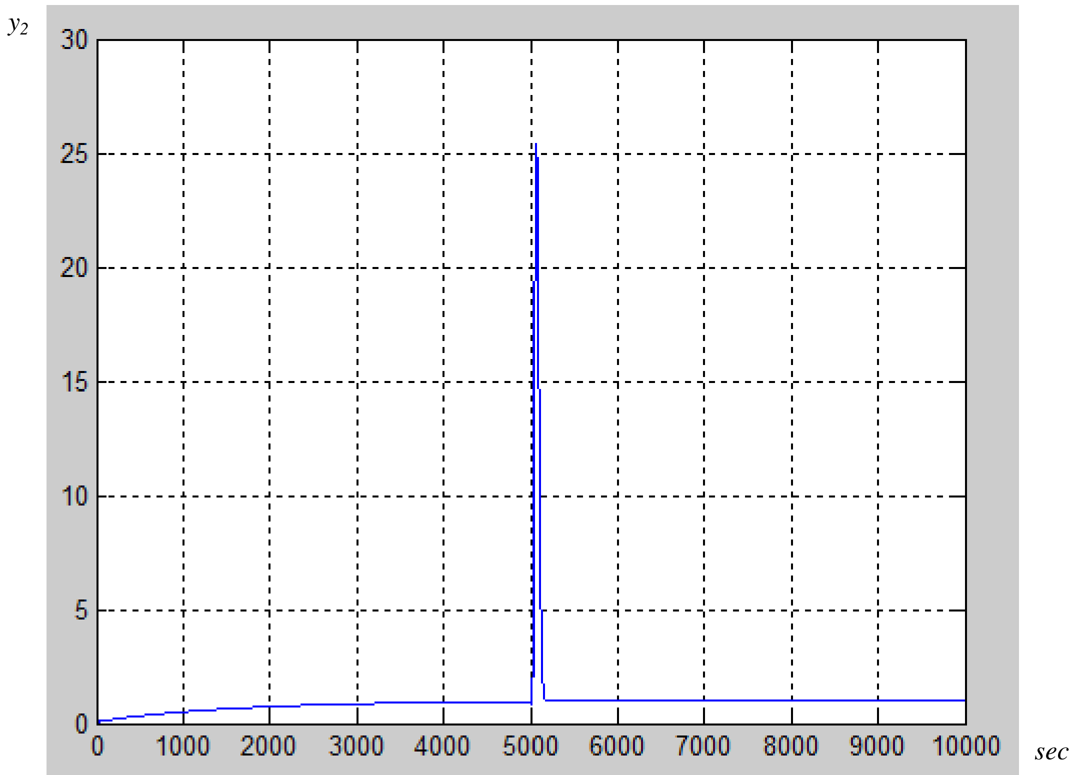

Figure-13. y_2 after fault accommodation and reconfiguration/ fault on second actuator.

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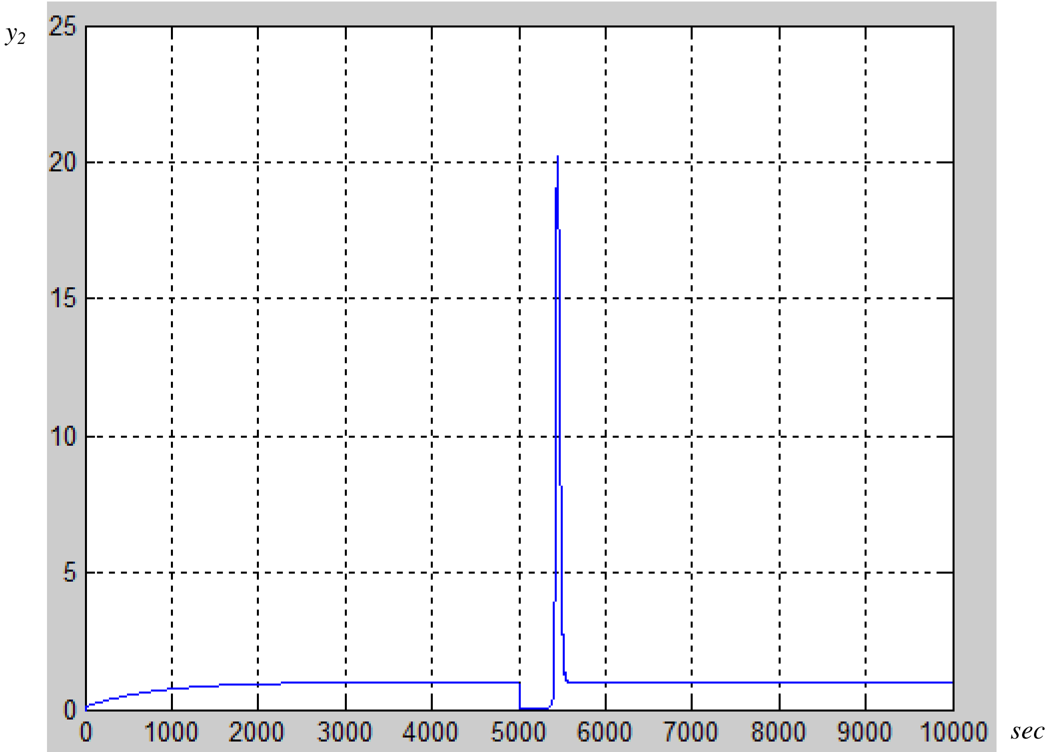

Figure-14. y_2 after fault accommodation and reconfiguration/ fault on first actuator.

As is seen, when the fault occurs, the system output experiences a sudden overshoot and the system approaches an undesirable response. However, having implemented the auto-tuning method of the controller coefficients, the coefficients are modified via an automatic process, and applying the modification method of Sigma, instantaneous oscillations resulting from exertion of changes have been reduced.

CONCLUSIONS

Since the FDI should first be accomplished for the system tolerance against faults, in this paper, fault detection and isolation was carried out by the use of the unknown input observers approach in multi-input multi-output system. The method makes it possible to isolate a fault using the structured residual with a little computational complexity. The method was used to detect faults in two actuators for the faults appearing as additives to the main system equations. In this method that is based on the system model and is quite applicable for multivariate systems, the main system is decomposed to several sub-systems in such a way that the effect other inputs is entered into the system state equations as a disturbance. The design method of the observer is such that the disturbance effect is attenuated while the fault related to a special input is only detected. Knowing the system state as well as its estimation, each one of residual shows the fault occurrence in the related actuator. It is worth mentioning that sensitivity of the observers to external disturbances is quite negligible. Next, when a fault occurred in one of the actuators and the system performance is affected by bad impacts resulting from the fault, the other controller coefficients are auto-tuned in an iterative manner, so that the modification method of Sigma is used to reduce oscillations resulting from instantaneous changes in the controller coefficients, which ultimately leads to the desirable stability and performance.

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